

**REPORT OF
DEPARTMENT OF DEFENSE
ADVISORY GROUP ON ELECTRON DEVICES**

**SPECIAL TECHNOLOGY AREA REVIEW
ON
OPTICAL CONTROL OF PHASED ARRAYS**



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PREFACE

In order to achieve ever greater force multiplying capabilities, the DoD is asking system designers to not only enhance the performance of the electronics in their systems but to make them lighter and smaller as well. One such system, the phased array radar, has recently become an object of interest to many researchers who believe that the heavy and bulky coaxial cables used in these radars could be replaced with lighter, thinner and better performing fiber optic cables.

As one of its many functions as an advisor to the DoD, the Advisory Group on Electron Devices (AGED) conducts Special Technology Area Reviews (STAR) to examine and assess technological areas of interest to the DoD. As a result of the attention recently given to optically integrated phased array configurations AGED Working Groups A (Microwaves) and C (Electro-optics) conducted a STAR on 12 March 1992. The report summarizes the information presented at the STAR and outlines the findings and recommendations that emerged from an extended review of the area by those working groups.

The editor wishes to express his sincere appreciation to all contributors—identified on the next page for their assistance and cooperation. This applies particularly to Palisades Institute for Research Services, Inc., for their assistance in the preparation of this report. In addition, it should be noted that the support and encouragement of Dr. John MacCallum, ODDR&E/AT has been essential to this effort.

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1. EXECUTIVE SUMMARY

Future DoD systems requirements will push current device electronics technology beyond its limits. Therefore, new technology will have to be developed to meet these requirements. One particular type of system, the phased array radar, has been given particularly stringent future requirements for size, weight, and performance. In an effort to try and meet these requirements several DoD agencies have conducted preliminary research in replacing the coaxial cable in current phased array radars with fiber optic cable. Unlike ordinary coaxial cable, fiber optic cable can carry an RF signal juxtaposed on a light wave, with very little attenuation or dispersion over wide frequency bandwidths. Furthermore, the fiber optic cable is mechanically more flexible and approximately 75% smaller and lighter than ordinary coaxial cable, allowing it to be assembled in more compact modules. Fiber optic cable is also impervious to harmful electromagnetic radiation. Consequently, fiber optic cables are presently being considered to replace the coaxial cable in phased arrays for such functions as RF signal distribution, phase shifter amplitude taper controls, true time delay beamforming and data transmission in systems with digital beamforming.

There are currently six programs in which RF-optical links are being researched. These programs are:

- Optically Controlled Phased Array Technology (DARPA co-funded with USAF/RL)
- High Speed Sources and Detectors for Fiber Interconnects (USAF/RL)
- Application of Microwave Photonics to Signal Processing and Antennas (USAF/RL)
- Optical Control of Microwave Devices and Circuits (ETDL/LABCOM)
- Fiber Optic Feed for Active Microwave Arrays (NRL)
- Optical Control and RF Signal Distribution to MMIC Phased Arrays (NASA-LeRC)

A review of these programs by AGED Working Group A yielded the following abridged findings and recommendations that are detailed in Section 5 (p.9):

- 1) **FINDING:** The Services and NASA are advancing the technology for optically controlled phased array systems, however, there still hasn't been a demonstration by which optical-based arrays can be compared to RF or digital-based arrays on the basis of cost or performance.

RECOMMENDATION: Increase coordination of existing programs within the DoD S&T community and develop validated cost and performance models. Continue funding at current levels but focus efforts in areas with higher system performance and/or cost benefits.

- 2) **FINDING:** Applications to active arrays will be limited to those cases where T/R modules are successfully inserted and where the requirements for transmit and receive channel performance can be met. Applications to receive-only arrays are limited by low noise amplifiers (LNAs), optical modulators/demodulators, dynamic range and cost.

RECOMMENDATION: Demonstrate and support by a thorough analysis of optical time delay and phase shift technology the potential performance and cost advantages of the integrated RF, optical and digital array system for specific applications.

- 3) **FINDING:** Because future phased arrays will require extremely light electronic/optical tolerance control the best of both optical and RF components will be required to meet overall requirements.

RECOMMENDATION: Establish joint Service and DoD programs to develop cost-effective processing techniques for incorporating RF, optical and digital capabilities onto one chip.

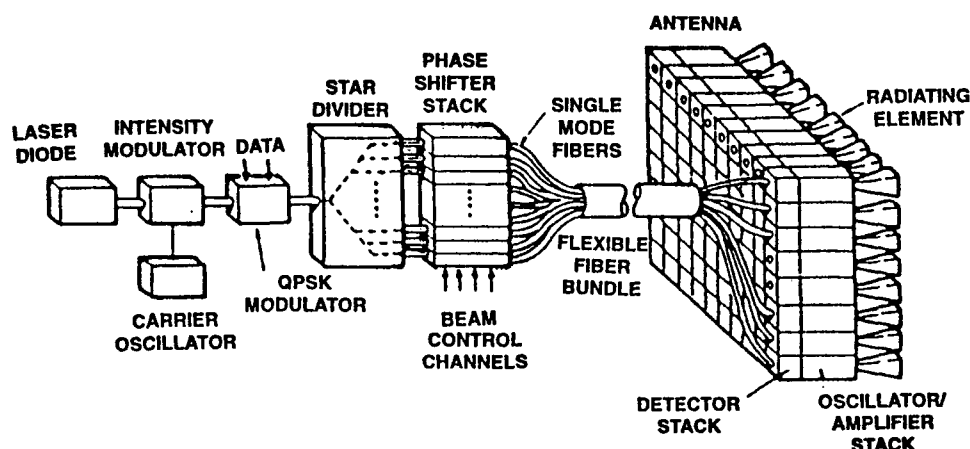
- 4) **FINDING:** The technology for optical transmission of digitally coded signals is available at transmission rates of up to 100s of megabits per second and has wide commercial applications. There is currently great interest in its application to digital beamforming and remote antennas. However, for some applications the dynamic range and sampling rate of the A/D converters may pose a limit.

RECOMMENDATION: Research and development should be continued with a focus on ultra wideband optical modulators and demodulators.

2. BACKGROUND

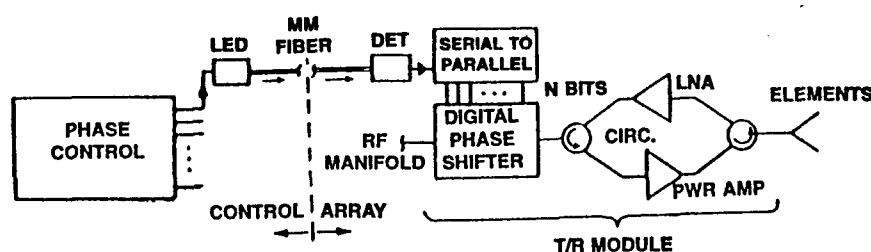
The well-known intrinsic properties of fiber optic cable make it a viable alternative to the coaxial cable used in present phased array radars. Unlike ordinary coaxial cable, fiber optic cable can carry an RF signal, juxtaposed on a light wave, with very little attenuation or dispersion over wide frequency bandwidths. Furthermore, the fiber optic cable is mechanically more flexible and approximately 75% smaller and lighter than ordinary coaxial cable, allowing it to be assembled in compact modules. Fiber optic cable is also impervious to harmful electromagnetic radiation. Consequently, fiber optic cables are presently being considered to replace the coaxial cable in phased array radars for such functions as RF signal distribution (Figure 1), phase shifter amplitude taper controls (Figure 2) and true time delay beamforming (Figure 3).

Figure 1

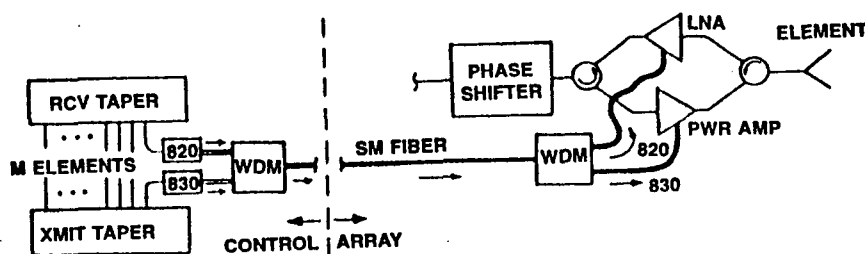


CONVENTIONAL ARRAY WITH FIBER OPTIC RF DISTRIBUTION MANIFOLD

Figure 2

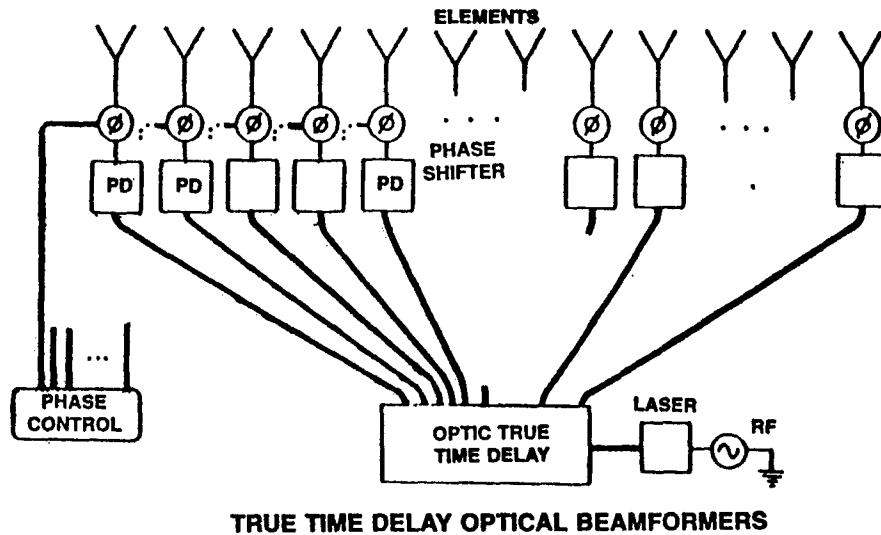


PHOTONIC CONTROL OF ELEMENT PHASE SHIFTER



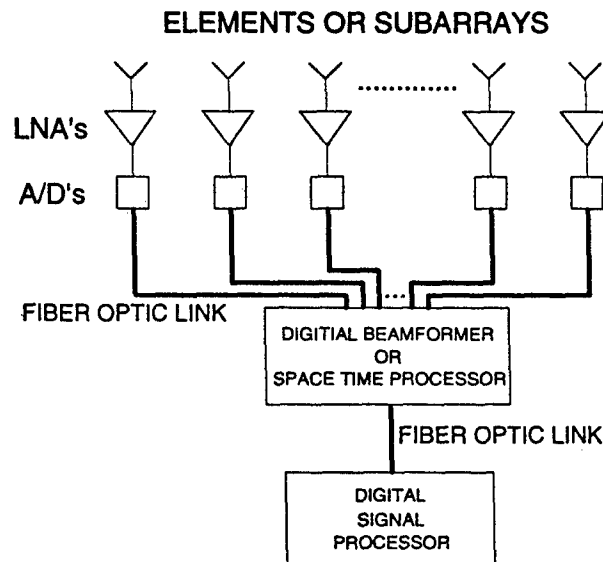
PHOTONIC CONTROL OF ELEMENT AMPLITUDE WEIGHT

Figure 3



There are, however, other less exotic uses for fiber optic cable that also deserve mention. For instance, most surveillance systems applying phase array antennas utilize digital beamformers as opposed to analog phase shifters/time delay units to form receive beams. This configuration allows the generation of multiple simultaneous receiver beams or a combination of receiver beams and spacial nulls by applying multidomain adaptive processing such as space time processing. Because the signal processing and beamforming in this configuration is entirely digital, the use of fiber optics is an obvious solution for the transmission of high data rate digital data between the analog to digital converter (A/D) output and the digital beamformer processor. A digital beam array with a fiber optic connection between the processor and digital beamformer is illustrated (Figure 4) as an example of an alternative configuration.

Figure 4



DIGITAL BEAM FORMING

The purpose of this STAR is to assess the feasibility of using optical technology in any of the above-mentioned configurations to meet future phased array radar system requirements. In order to make this determination, future radar system requirements will first be examined, followed by a status report on the technology needed to meet these future requirements. Based on this information, AGED Working Groups A and C have developed a number of recommendations indicating possible courses of action for the DoD.

3. SYSTEM REQUIREMENTS

Phased array radars under development or being proposed must meet a variety of surveillance requirements. Demands placed on the signal distribution and control components are driven by the requirements of certain applications. Long-range airborne early warning (AEW), airborne intercept (AI) and precision strike are specific applications that are currently of great interest to the DoD which place some of the most stringent requests on the components. Generally, these radars must be capable of detecting and tracking small targets while operating in a high-clutter, multiple-jammer environment. Tables 1 and 2 indicate the issues and the required increase in performance of future systems over current fielded systems.

Table 1. Critical Surveillance Issues and Requirements

ISSUES	SUBISSUES	REQUIREMENTS OF FIELDDED SYSTEMS	REQUIREMENTS OF YEAR 2000 SYSTEMS
Subclutter Visibility	System (dynamic range)	55 dB	90 dB (15 bits)
	Antenna sidelobes (1 way)/Aircraft	-55 dB on test range	-55 dB on Aircraft
	Stability (dB below carrier)	100 dB	150 dBc/Hz at 1 kHz from carrier
Multi Jammer Rejection	Mainlobe cancellation	—	-60 dB to -70 dB
	Dual-band radar	—	Validated technology

Table 2. Critical Airborne Intercept Radar Issues and Requirements

ISSUES	SUBISSUES	REQUIREMENTS OF FIELDIED SYSTEMS	REQUIREMENTS OF 2000 SYSTEMS
Aperture Taper	—	Fixed	Selectable
Antenna (Directive Gain)	—	35 dB to 40 dB	35 dB to 40 dB
Multimode	Low sidelobes	~ 100 dB (2-Way RMS)	~100 dB (2-Way RMS)
	Pattern flexibility	Mechanical scan	Electronic scan
	Noise level (@ 1 kHz)	-95 dBc/Hz to 105 dBc/Hz	-102 dBc/Hz to 130 dBc/Hz
	Rcvr 3rd order intercept	+20 dBm	+20 dBm
	Large dynamic range	60 dB	90 dB
Bandwidth	—	~5%	20% to 30%
ECCM	—	Processor software	Waveform, frequency diversity

Other phased array applications such as imaging radar or space communications stress the bandwidth capability of components. It is critical that the specific application-performance requirements be considered when array signal and control techniques are selected.

It must be remembered that to meet the system requirements indicated in the previous charts the performance of each component in the entire chain must exceed the requirements for the entire system. For example, a receiver array or an active array in the receive mode for airborne intercept radar typically consists of hundreds of receiver channels. Antenna sidelobe specifications require amplitude and phase (or time delay) variations between these channels of less than 0.2 dB and 1.5 degrees, making it necessary that the devices perform better than the requirement.

In order to cost-effectively satisfy future requirements for both surveillance and airborne intercept functions, future phased arrays radar systems must meet the following requirements:

- **SIDELOBES** — Down -20 TO -60 dB (Implies a few degrees of phase error, 0.5 dB amplitude error)
- **DYNAMIC RANGE** — To 90 dB (15 bits)
- **POWER X GAIN (EIRP)** — 10 to 100 watts/element
- **NOISE** — 3 dB noise figure
- **BANDWIDTH** — In the GHz range for radar and communications
- **SWITCHING SPEED** — Microsecond, accurate ferrite devices; and nanoseconds, accurate diode devices
- **COSTS** — \$100/element (passive) and \$500-\$1000/module (active)

4. TECHNOLOGY STATUS

There are currently six programs in which RF-optical links are being researched. Those programs are:

- Optically Controlled Phased Array Technology (DARPA co-funded with USAF/RL)
- High Speed Sources and Detectors for Fiber Interconnects (USAF/RL)
- Application of Microwave Photonics to Signal Processing and Antennas (USAF/RL)
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- Fiber Optic Feed for Active Microwave Arrays (NRL)
- Optical Control and RF Signal Distribution to MMIC Phased Arrays (NASA-LeRC)

The research being conducted under these programs can be divided into four distinct areas: high speed sources, optically processed beamforming, integrated MMIC laser detectors, and optical RF phased array feeds. These four areas are discussed in detail below.

High Speed Optical Sources

Research in high speed optical sources is being conducted by USAF/RL at the 6.1 (basic research) and 6.2 (exploratory development) level and can be broken down into two smaller categories: directly modulated lasers and waveguide modulators.

Three semiconductor laser types based on indium phosphide are presently being researched for directly modulated optical sources: the mass-transported buried heterostructure (MTBH) laser, the strained-layer multiquantum well (MQW) laser and the vertical cavity surface emitting laser (VCSEL). The MTBH laser which is available in a fully packaged module capable of broadband analog modulation to 20 GHz is the most advanced and is widely used in commercial telecommunications. Work is presently under way to raise the modulation rate of the MTBH to 25 GHz. The strained layer MQW laser has been demonstrated to 28 GHz and has potential to go beyond 40 GHz. First-generation VCSELs have demonstrated 8 GHz modulation but are theoretically limited to modulation rates approaching 40 GHz by thermal and gain saturation effects. Problems of high series resistance, linearity, packaging and relative intensity noise (RIN), which determine the insertion loss and dynamic range of the optical link, are being investigated. A gallium arsenide-based VCSEL is also being developed.

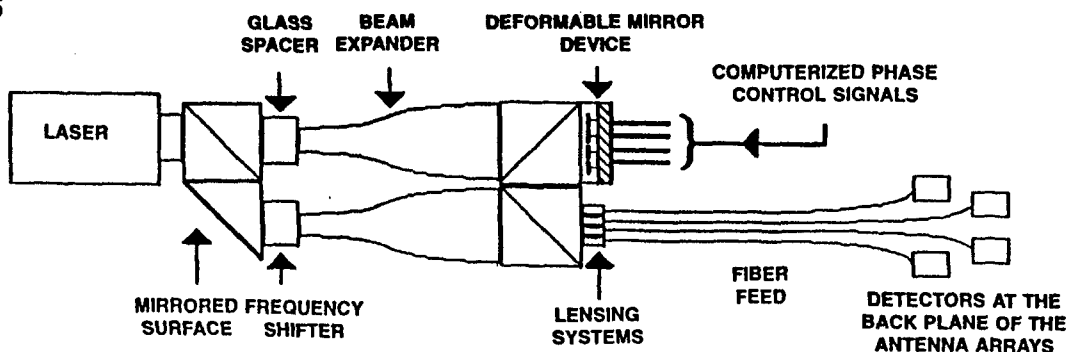
Gallium arsenide-based travelling-wave optical modulators are being developed for performance to 100 GHz. The limiting factor in high-speed modulation of these devices is typically velocity mismatch between the optical and microwave signals. This mismatch can be eliminated to the first order in these devices by burying the microstrip under a GaAs superstrate. State-of-the-art lithium niobate modulators are limited by velocity mismatch to approximately 18 GHz but can be extended to beyond 30 GHz by properly designing the device. Lithium niobate devices are subject to optical damage at wavelengths less than 1 μm .

High-speed guided-wave modulators are also being investigated at ETDL. Velocity-matched GaAs modulators are being developed for use at millimeter-wave frequencies. Carrier effect (depletion) devices are also under investigation.

Optically Processed Beamforming

The effort to develop methods for achieving phased array beamforming with optical devices is presently being conducted by USAF/RL and NASA-LeRC at the 6.1 and 6.2 levels. There are three different designs presently being considered: a 20 element (L-band) spatially integrated beamforming system (Figure 5), a continuously variable RF delay for a spatial optical processing system and a 20 element reconfigurable RF/microwave filtering system. There has also been additional research to replace deformable mirror devices (DMD) with electro-optic devices and to investigate the possibility of using electrical and/or optical feedback for closed-loop filtering applications.

Figure 5



SPATIALLY INTEGRATED ADAPTATION

Integrated MMIC Laser/Detector

Research on integrated MMIC laser/detectors is being conducted at USAF/RL, NASA-LeRC, and ETDL/LABCOM. However, whereas the efforts at the Air Force and NASA are part of larger programs (described below), the Army has a program devoted specifically to the device area. The Army is acquiring experimental data on MESFET optical detectors to be used to control gain and phase, and to perform switching, frequency tuning and injection locking.

Optical RF Phased Array Feeds

Most of the work in the area of optical RF phased array feeds is at the 6.2 - 6.3 (advanced development) level. The USAF/RL has a fully integrated program which has demonstrated a 32 element array and is presently developing a 96 element conformal array, including integrated delay lines. USAF/RL is also conducting research into holographic optical elements in a Rotman lens beamformer. The RL group plans to test this new conformal array in FY94. The program is funded at \$12M through FY94, with the FY92 breakdown as follows: AF 6.2 (\$1.4M), AF 6.3 (\$3.1M), and DARPA (\$3.2M). The ETDL/LABCOM (SDC) effort funded by the Strategic Defense Initiative (SDI), is working on fiber optic controlled phased array technology (FOCPAT). It is a 50-Month effort with a contract ceiling of \$5.7M. Currently, it is funded at a very low level and only the analysis phase has been completed thus far. NRL, which conducts most of its research in this area in-house, has a demonstration that is still in the planning stage. NASA-LeRC has millimeter-wave and high speed digital programs that are investigating designs that integrate MMIC and optical technology for space communications application.

5. FINDINGS AND RECOMMENDATIONS

(1) FINDING:

The Services' and NASA's programs are advancing the device and component technology and it is at the stage where the first array demonstrations can be made to evaluate the performance-level capabilities of optically controlled phased array systems. Once the performance capabilities have been assessed they must be compared to projected RF or digital-based arrays in cost and performance at which point the ultimate potential for this technology must be assessed. When making the comparison it is also important to consider ancillary subsystems such as power supplies, etc. Without validated array performance information within specific application requirements, optical technology will have minimal system impact.

RECOMMENDATION:

Increased coordination of existing programs and joint programs within the DoD S&T community should be established. NASA and other DoD technology efforts such as the Army SDC work should be included. The joint work should develop validated cost and performance models for use by systems designers as well as in evaluating the benefits of a specific technology. The level of funding required to generate the precise information desired by array product developers makes jointly funded cooperative efforts critical to the successful implementation of field systems.

Device/component R&D funding should continue at current levels. Efforts should be focused in areas with higher potential system and/or cost benefits.

The focused array system programs of the Air Force should be funded at a level and a rate adequate to complete the technology evaluation on schedule. Emphasis should be placed on array-level parameter measurements and should include dynamic range and channel-to-channel performance variation evaluations.

(2) FINDING:

Optical time delay and phase shift technology is making excellent progress in some applications. However, application to active arrays will be limited to those cases where T/R modules are successfully inserted and where the requirements for transmit and receive channel performance can be met. Applications to receive only (or passive) arrays are limited by LNAs, optical modulators/demodulators, dynamic range and cost goals. The long-term competition of optical beamforming is digital beamforming, not analog beamforming.

RECOMMENDATION:

Optical time delay and phase shift technology must be demonstrated in radar and communication array systems. The demonstrations should be supported by a thorough analysis of the potential performance and cost advantages of the integrated RF, optical, and digital array system for the specific application.

(3) FINDING:

High performance applications require extremely tight electronic/optical tolerance control (very well matched phase/time delay and amplitude). The best of both optical and RF components will be required to meet overall phased array requirement. The key to success will be a new and improved generation of RF and optical (as well as digital) components on one chip to allow the very precise component interfaces required at an affordable cost.

RECOMMENDATION:

Strong DoD tri-Service coordination, leading to joint Service and DoD funded programs, should be encouraged to develop effective chip processing techniques that will provide chips with RF, optical and digital capabilities and will emphasize cost-effective interface circuit technology.

(4) FINDING:

The technology for optical transmission of digitally coded signals is available up to 100s of megabits per second and has wide commercial applications. There is currently great interest in its application to digital beamforming and remote antennas. However, for some applications the dynamic range and sampling rate of the A/Ds may pose a limit.

RECOMMENDATION:

Research and development should be continued with a focus on ultrawideband optical modulators and demodulators.

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